RIMFIRE: A SIX MEGAVOLT LASER-TRIGGERED GAS-FILLED SWITCH FOR PBFA II*

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Abstract

We have developed a new multiple-stage laser-triggered SF_6 spark gap, which has performed well in tests at nearly 6 megavolts and half a megampere. It has survived many hundreds of shots between 5 and 5.7 MV, the highest voltage tested. A 25 millijoule ultraviolet laser pulse arriving in its trigger gap reliably closes the whole switch in 20 nanoseconds with 0.4 ns 1-sigma jitter. The closing time has a low dependence on the applied voltage, about 0.9 ns/% of self-break voltage. For a 10 mJ laser pulse, the jitter is 1.5 ns and the slope is 1.0 ns/% . No prefires have occurred; the estimated prefire rate at 90% of self-breaking voltage is less than 0.1%. The switch inductance is 400 nanohenries, of which about 100 nh comes from the spark channels. The switch is 68 cm long and 61 cm in diameter.

Introduction

The second Particle Beam Fusion Accelerator (PBFA II) is a 100 Terawatt lithium ion accelerator now being built at Sandia to study inertial confinement fusion.[1] It requires 36 gas switches to be triggered by a single ultraviolet laser. Each switch must hold off up to 6 MV for a microsecond and then fire into a 4 ohm load with 1 nanosecond jitter or less. The prefire rate at the highest operating voltage must be less than 0.1%. The switch must be less than 70 cm long and function in a deionized water dielectric. The inductance must be about 400 nh. We have designed and tested a multiple-stage gas spark gap which meets these requirements. We are now assembling 36 of the switches for laser-triggered tests in PBFA II this summer (1985).

Developing such a switch has not been easy. Several years ago the highest voltage available on a triggerable gas switch was about 3 MV. An example of such a switch is the trigatron we used in the first particle beam fusion accelerator, PBFA I.[2] These single-gap devices had two main electrodes and a small trigger electrode in the anode. On a trigatron with an 11 cm gap filled with sulfur hexafluoride (SF_6) at 60 psia, the self-breakdown voltage was 2.9 MV.[6] It had a field enhancement factor of 1.44 on the cathode and 1.59 on the anode. When triggered with a 60 kV pulse at 90% of the self-break voltage, the main gap broke down about 90 ns later. Under optimum trigger conditions the jitter was 2.0 ns. Triggering a similar (2.5 MV) gap with an ultraviolet laser pulse reduced the jitter to about 0.5 ns under the best conditions, but the laser energy needed was rather high, about 120 mJ.

Simply scaling up the trigatron to 6 MV would not meet the PBFA II requirements. The gap would have to be more than twice as long, making the jitter, inductance, and laser trigger energy unacceptably high. Consequently, we began to consider multiple-stage designs similar to one designed by Physics International for their EAGLE machine and tested by Sandia in 1980.[3] It was a 3 MV switch with about 2 ns jitter. One advantage of multistage designs is that they can be scaled up more easily simply by adding stages.

First Multistage Design

Figure 1 shows the first multistage switch we tried.[4] It was essentially a scaled-up and triggered version of a design E. L. Neau had developed for 3 MV use.[5] The new switch had low jitter and laser trigger energy, but it failed at about 4 MV, well below the 6 MV design level. The insulators would frequently flash over at the water/plastic interface, destroying them. The electric field on the insulators just before switch firing was rather low, about 70 kV/cm.

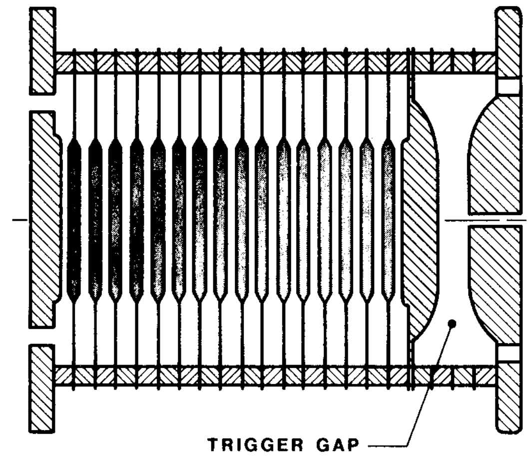

Figure 1. First multistage switch.

After running some computer simulations, we began to suspect that the problem was related to the basic electrical response of the switch; each stage formed a high-Q resonant circuit that oscillated for microseconds at 50 MHz or more.

Experimental evidence for the existence of these oscillations was found in open-shutter photographs which showed water streamers of equal length going in both directions (toward anode and cathode) from the electrode rim of each stage. In water, positive streamers propagate considerably faster than negative streamers, so there must have been a sustained AC voltage across each stage in order for the streamer length to be the same in both directions. To confirm this, we put external spark gaps in the water across each stage. We set the gap spacings so that they would fire about 300 ns after the last gas gap closure. This was relatively late, about 150 ns after the total switch current stopped. Water gaps have greater losses than gas gaps. When the auxiliary gaps fired at the proper time, they suppressed the bipolar streamer growth, indicating that they were clamping an AC voltage which still existed across the stage after 300 ns.

The Rimfire Concept

These problems stimulated an idea for a new type of multiple-stage switch. Our basic concept was to electrically isolate the electrodes from the outer housing.

It has three important advantages:

(1) protect the outer housing from high voltage transient,
(2) lower stage capacitance, and
(3) reduce run time due to shorter current paths.

Physical Description

Figure 2 shows the present design. A central stack of 7.6 cm Lexan discs, about the size of hockey pucks, supports 15 toroidal electrodes. Compressive forces from plastic rods outside the housing hold the stack together. A spring consisting of Belleville

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14. ABSTRACT
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washers in one of the base plates keeps a compressive force on the central stack. Each of the fifteen identical gaps is 1.27 ± 0.01 cm. The electrodes are annealed bead-blasted stainless steel, 21.6 cm in major diameter. The bead blasting roughens the electrode so that its characteristics will not change after sparks damage the surface. Also, microscopic glass fragments imbed themselves in the annealed surface; the discontinuities between glass and metal provide reliable starting points for streamers and thus reduce the statistical delay.[6] With 6.0 MV across the switch the voltage across each gap is about 325 kV. The maximum static field in a gap is 284 kV/cm, about 10% higher than the average field. The point of maximum field is very near the rim, so that discharges tend to occur near or on the outer curved surface. This helps the electrodes to shield the insulating disc from metal splattering and ultraviolet light. Each disc is 2.86 cm high, and the static field along its surface is about 115 kV/cm. The capacitance between stages is about 25 pf, about twenty times smaller than the previous switch interstage capacitance.

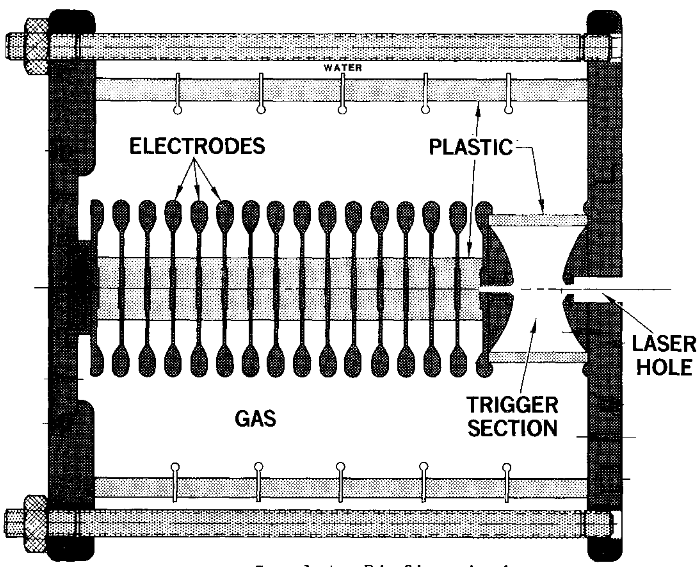

Figure 2. Complete Rimfire design.

The trigger section consists of two hemispherical electrodes separated by a 5.7 cm gap. The electrodes are stainless steel, except for refractory metal inserts in the center. The inserts are shrink-fit in place and held with screws in back. Then we machine the surface and bead-blast it to insure that there is no discontinuity between the inserts and electrodes. The inserts are made of Mallory 1000, a metal consisting of 90% tungsten, 6% nickel, and 4% copper. It has a high melting point, high thermal and electrical conductivity, and a high mass density.

The laser beam enters through a 1.9 cm diameter hole in the anode and comes to a focus in the center of the gap. A 0.95 cm diameter hole in the cathode allows an auxiliary beam of visible laser light to illuminate the plastic disc in the first Rimfire stage. This allows the machine operator to easily check the beam alignment during setup or maintenance periods. With 6.0 MV across the switch, the trigger gap voltage is about 1.25 MV. The maximum static field on the electrodes is on the rims of the laser holes, about 300 kV/cm on the anode and somewhat less on the cathode. Moving along the central axis, the field rises from a low value in the laser hole up to a maximum of about 200 kV/cm in the center of the gap. Figure 3 shows a plot of electric fields in both the Rimfire and trigger gaps.

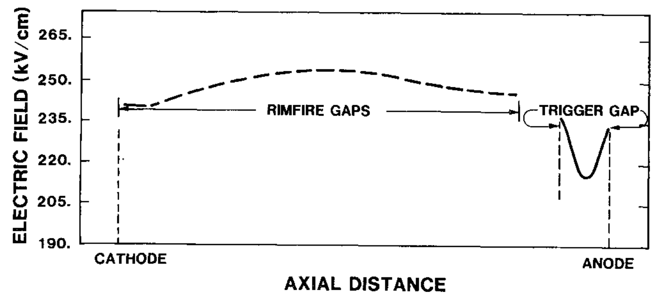

Figure 3. Electric field strengths in gaps.

The trigger section insulator is a Lexan cylinder with an inner diameter of 15.2 cm and a height of 12.1 cm. It must withstand a high-shock environment as well as the electric field. Grooves in its inner and outer surfaces make the creepage path longer. Shields protect the triple points at the ends of the cylinder from ultraviolet light, metal splattering, and high electric fields. The static field at the ends is about 65 kV/cm; the maximum field is 115 kV/cm in the middle.

The outer housing consists of six lucite cylinders and five aluminum grading rings containing O-rings between the lucite pieces. A small toroidal shield on the side of the grading rings reduces the field at the triple points and protects them from ultraviolet illumination. Recesses in the two base plates shield the triple points at the ends. The maximum field is 115 kV/cm.

Laser and Optics

The laser system used to test the switch is a KrF oscillator-amplifier combination operated in an injection-seeded mode with an unstable resonator optical cavity. It generates an ultraviolet beam of 248 nm wavelength, divergence half-angle of about 75 microradians, and a pulse width of 20 ns. Partly transmitting dielectric-coated mirrors attenuate the beam energy, simulating the beam energy in PBFA II. Eight dielectric-coated turning mirrors direct the beam about 30 m through a quartz window to the anode end of the switch. A 50 cm focal length plano-convex quartz lens focuses the beam into the middle of the trigger gap. The operators align the long optical system using a visible laser beam coaxial to the UV laser beam path, retro-reflective tape on the borders and backs of the optics, and an auto-collimating telescope. The visible beam passes through the trigger gap into the hole in the cathode and illuminates the Lexan disc on the other side. This provides a simple alignment check, as we mentioned in the previous section. Several previous articles describe the laser system in more detail.[7]

Electrical Operation

Figure 4 is an equivalent electrical circuit for the switch. A Marx generator charges the storage capacitor C_0 through an inductance L_0 toward a peak voltage of about - 6 MV, taking about 1100 ns to do so. It also charges up the Rimfire gap capacitances, C_1 through C_{15}, the trigger gap capacitance, C_t, and the stray capacitance C_s outside the switch in the water. The capacitance ratios are such that about 20% of the voltage is across the trigger gap. Since the load resistance R_L is low, it keeps the voltage at the switch anode less than a few percent of the charging voltage.

When the voltage across the switch exceeds a few MV, streamers begin to form at the cathode of each gap. At first they move slowly, but as the voltage nears the operating level they begin to accelerate.[8]

At a time when the voltage is about 90% of self-break, we fire the laser. The concentration of ultraviolet light ionizes the SF_6 gas near the focal point, producing a needle-shaped laser spark a few centimeters long along the axis of the gap. The presence of the conductive spark enhances the electric fields in the gap, accelerating the streamer growth greatly. The uniformity of electric fields (Fig. 3) in each gap is important; it insures that each gap is equally ready to fire at the time of triggering.

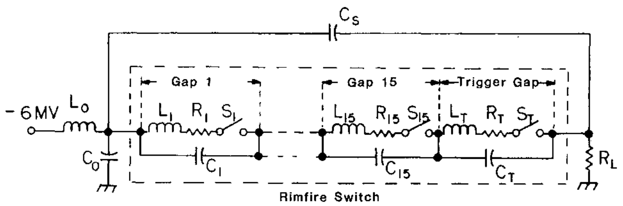

Figure 4. Electrical model of Rimfire.

Within about a nanosecond, the trigger gap breaks down; we simulate the breakdown in the model by closing switch S_t. The trigger gap capacitance C_t begins discharging rapidly through the spark channel inductance L_t and the spark channel resistance R_t. This sudden decrease of voltage increases the total voltage across the Rimfire gaps by more than a megavolt. The overvoltage travels as a wave toward the cathode. It begins breaking gap 15 down first and then the others in sequence. When gap 15 breaks down completely, switch S_{15} closes and begins discharging the gap capacitance. This applies yet more voltage to the remaining gaps.

Since the Rimfire gaps have much less capacitance than the earlier design, they discharge much faster. The greater dV/dt of gap 15 applies voltage to gap 14 faster. Also, current from gap 15 only has to travel a few cm to reach gap 14. These two factors greatly reduce the time it takes to break down gap 14. In this way a rapid wave of discharges travels down the whole switch.

Because the breakdown times are so short, several streamers in each gap manage to close independently of each other, producing multiple spark channels in each gap. The voltage across each gap oscillates the way we described earlier. The oscillations continue until shortly after the last gap closes, about twenty nanoseconds after the laser energy first arrives in the trigger gap. This short continuation of oscillation is beneficial, because it maintains discharges in the gaps until current starts going through the switch as a whole. (The laser light also continues for about twenty ns after starting.) However, the oscillations do not continue much longer than the switch closing time, thus sparing the insulators unnecessary stress.

Once the switch as a whole is closed, C_0 begins discharging into the load. A current of about 500 kA flows for about 150 ns, after which the current stops and the switch's main function is finished, although some energy is reflected from the load later.

Performance

Figure 5 is an open-shutter photograph of the switch firing. The average number of spark channels per stage is between 3 and 4. Often the sparks appear to leap from rim to rim across several stages, producing a line of discharges. The stainless steel Rimfire electrodes show only moderate erosion after hundreds of shots. The stainless steel trigger electrodes, however, eroded severely when we first tried them. The vaporized steel condensed on the trigger insulator and shorted it after few shots. The problem stopped when we inserted Mallory metal in the area of discharge. We found that a good electrical contact between the insert and the steel is necessary to prevent small arcs at the interface, which contribute their own splattering. The contrast between the Rimfire and trigger electrode erosion is probably due to the different current densities. Running 500 kA through the single spark channel in the trigger section was enough to vaporize stainless steel. But splitting the current into several channels in the Rimfire gaps apparently reduces the current density below some critical value, leaving the stainless steel relatively undamaged.

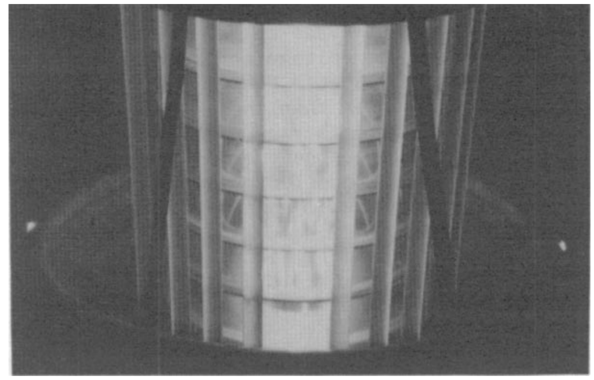

Figure 5. Open shutter photo of Rimfire discharging in demonstration module.

Figure 6 shows how the self-break voltage depends on the gas pressure. There are sixteen data points on the Version 1 curve; many of them overlap each other. Version 1 had a somewhat different trigger section than Version 2, the latest. The theoretical points are from T. H. Martin's model.[8] The standard deviation of this run, 50.3 kV, was unusually good, indicating a self-break sigma of about 1% at 5 MV. All the runs give a sigma of less than 3%, except for one in which an electrode was not properly seated on an insulator disc. A self-break sigma of 3% is enough to make the prefire probability less than 0.1% at 90% of self-break voltage.

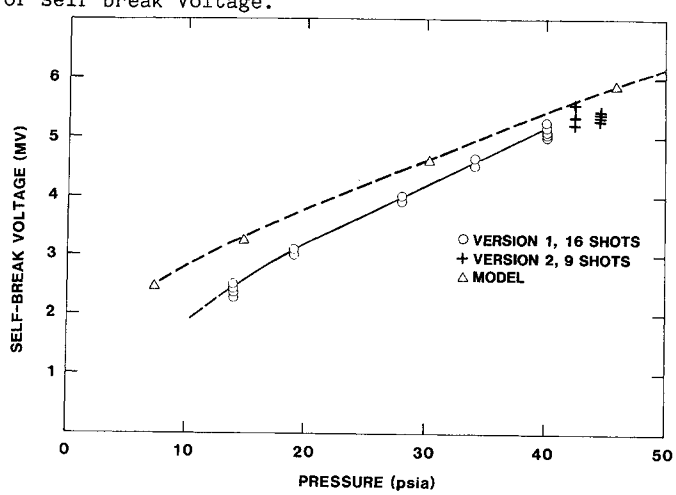

Figure 6. Self-break Voltage of Rimfire versus pressure.

Figure 7 shows how the switch closing time depends on the voltage. The gas pressure is 0.34 MPa (50 psia), corresponding to a self-break voltage of 5.7 MV. The laser energy arriving in the trigger gap is 25 mJ. Zero represents the time laser energy begins to arrive. The lower set of data points show the closing time of the trigger gap, as determined by fluorescence. The upper set of points show the closing time of the whole switch, as determined by current flow in the load. The jitter and slope of the switch, 0.4 ns and 0.9 ns/%, are well within specifications for PBFA II. We made a number of similar tests giving similar results. The jitter of

the total switch is about the same as that of the trigger gap. This indicates that once the trigger gap fires, the overvoltage is enough to assure rapid firing of the Rimfire gaps. In order to determine the limits of triggering, we made some tests with a relatively low trigger energy, 10 mJ. The resulting jitter and slope for the whole switch were 1.5 ns and 1.0 ns/%.

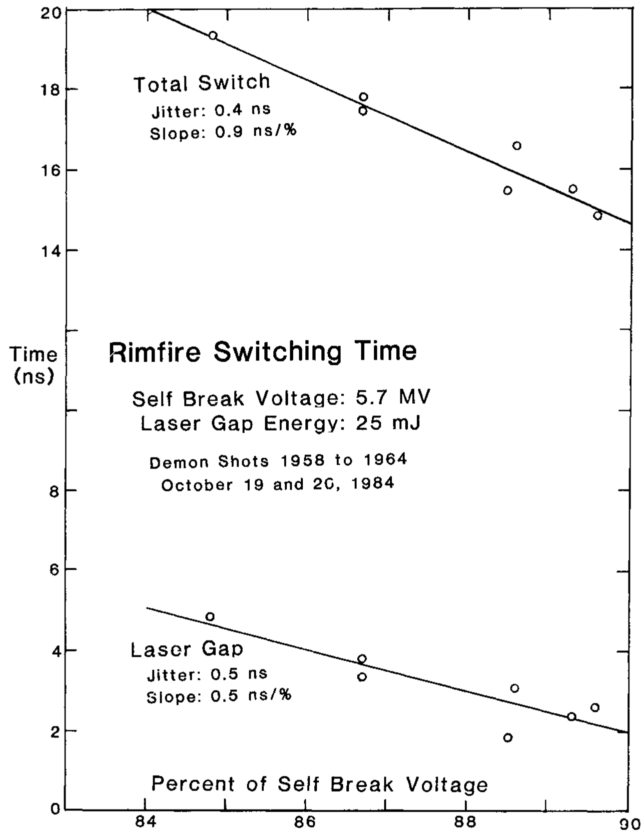

Figure 7. Closing time of Rimfire versus % of self-break voltage.

The latest version of the switch has experienced over one hundred shots above 5 MV with no failures. The most rigorous shot was a "ringover" at 5.7 MV. In this shot the gas pressure was over 50 psia, enough to prevent the switch from firing at the peak machine voltage of 5.7 MV. The voltage went past the peak and the switch did not fire until hundreds of nanoseconds later. This exposed the switch to maximum voltage for much longer times than normal operation. The only abnormality was a low-energy nondestructive discharge on the gas side of one of the housing rings. We continued to use the ring after that shot.

Discussion

We have learned a number of things which could be useful to people designing high-voltage switches. The most surprising lesson to us was the importance of minimizing interelectrode capacitance and oscillations in multistage switches. Such problems do not show up in single-gap switches because the resonant circuit of the gap is directly connected to the source and load impedances, thus damping the oscillations. But since a gap in a multistage switch is only loosely connected to source and load through the other gaps, it is free to oscillate for long times.

We also learned a few things to avoid in the trigger section. An early version of the trigger section had only 15% of the total voltage across it. The maximum field in the trigger gap was only about 80% of the maximum field in the Rimfire gaps, and the field in the trigger gap center was considerably below that. The gap was longer than the present gap. The jitter and slope with that design were quite a bit worse than the present design. The percentage of the switch voltage controlled by the trigger section determines the overvoltage applied to the first Rimfire gap: a factor of 3 is not enough, but a factor of 4 is. It is also important that the trigger gap should be short enough to be dominated by the laser spark length, and that the trigger gap and Rimfire gaps should have nearly equal fields. To insure that self-triggering begins in the trigger gap, its field should be a bit higher than the others.

A third item is the distinct threshold for damage to electrodes we encountered. Half a megampere for 150 ns concentrated in a single spark severely damaged stainless steel (but not Mallory 1000). The same current divided among several sparks produced much less damage to the steel. A fourth item related to this is that insulators can withstand high voltages within a few inches of high-current arcs, but shielding the triple points from splattering, ultraviolet light, and high fields is necessary.

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